AC 2011-1530: MODEL-ELICITING ACTIVITIES IN A MECHANICAL ENGINEERING EXPERIMENTAL METHODS COURSE

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Using Model-Eliciting Activities in a Laboratory Course on Mechanical Instrumentation

Abstract

Model Eliciting Activities, or MEA's, are an extension to inductive learning which add additional guidance to help ensure that students learn not only skills in teamwork, project management and communication but also the technical competencies of engineering. Two MEA's developed for use in a Senior level undergraduate mechanical engineering course are discussed herein. The first MEA in this course on mechanical measurements involves the design of a strain gauge based load cell transducer. The second MEA involves the use of an accelerometer to compare the impact absorbing properties of packaging materials. Both MEA's were implemented in the Winter 2010 quarter; the effectiveness of the MEA's for student learning, student responses to the MEA's, and lessons learned are discussed.

Introduction

In the senior level undergraduate mechanical engineering curriculum at California State Polytechnic University, San Luis Obispo, we are striving to step away from recipe driven, step-by-step instructional laboratories and to provide students with problems that have more professional engineering context. A common method to provide more realistic and open-ended problems is Project-Based Learning (PBL). PBL has recently been gaining wide acceptance among engineering administrators, and many faculty are moving in the direction of adopting more PBL based techniques into our courses. Key features of PBL are the involvement of students in open-ended "real-world" problems which are sometimes developed in conjunction with industry partners, and a change in the role of faculty from that of organizing, distilling and efficiently disseminating content to a role of coaching students as the students find and organize information themselves. Although the resemblance of PBL projects to real-world projects has been shown to have advantages for student motivation, the encouragement of lifelong learning[1], and other "soft skills" such as teamwork, there are disadvantages as well. In addition to the increased faculty workload associated with PBL[2], there are difficulties for faculty working in a PBL environment in ensuring that students reliably learn core technical competencies[2,3]. A further concern is that when projects for Project-Based Learning are sponsored by industry, projects may be chosen to optimize financial results for the institution rather than learning outcomes for the students.

Model Eliciting Activities, or MEA's, provide a framework which assists the design of projects which ensure that students meet learning outcomes associated with professional competence as well as problem-solving and communication skills[3]. Projects designed as MEA's share many of the same characteristics as other Problem- and Project-Based Learning activities, such as the assignment of open-ended problems which are (or closely resemble) tasks performed in professional practice. However, MEA's are built upon six guiding principles that differentiate them from PBL. The guiding principles of MEA's are as follows:

1) *The Reality Principle:* The task provided to students should be of a type, and be posed in a context, which could occur in professional practice. Students should be able to make sense of the situation based on extensions of their own personal knowledge and experiences.

2) *The Model Construction Principle:* The task must create the need for a model to be constructed, modified, extended, or refined. For example, the model could be a mathematical model, a decision algorithm, or a computer program. The requirement for a model is an important way to ensure that the students are required to utilize a significant degree of technical competence in solving the problem.
3) *The Self-Assessment Principle:* Criteria for self-assessment must be clear. Students must be able to determine for themselves when their solution meets the needs of the client and when the model is "good enough."
4) *The Model-Documentation Principle:* The students must document their solutions, typically in the form of a written memo to the client. Deliverables might also include hardware, a student-created video, or a computer program.
5) *The Generalizability Principle:* The model should be applicable to a broader range of similar situations than just those presented in the problem statement. This ensures that the students learn concepts rather than just specific solutions.
6) *The Effective Prototype Principle:* The concepts that students must formulate, construct, modify, etc. must be robust in terms of their applicability to the future academic and professional life of the engineering students. A high-quality MEA will help students work with several important and common concepts.

In a course on mechanical measurements at California State Polytechnic University, we have used the MEA principles to develop a series of assignments which require teams of students to solve problems of a scope and nature very similar to that which they are expected to encounter in their engineering careers. To successfully solve these problems, the students must work in teams, understand the physical principles relevant to the problems, design solutions using their understanding, consider the ethical implications of their designs, and interact with the customer through verbal and written communication means. Two of these assignments are discussed in this paper: the design of a force transducer for medical rehabilitation, discussed in detail, and the design of an accelerometer based impact measurement system for a package delivery company.

Load Cell Transducer MEA Exercise

In this MEA, teams of two or three students are assigned to work as engineering consultants for the owner of a fictitious company, "Rehab-o-Rama", which manufactures physical rehabilitation equipment. The students are given a memorandum from the owner, requesting that the students design a class of load cell transducers to be used to measure the force generated by a rehabilitation patient. As the required capacities of load cells for which the students' design method must be usable vary from 5 to 100 pounds, a single design is not acceptable; the students must create a design algorithm. The algorithm is then used to design a single transducer which the students build, calibrate, and test in the laboratory. The memo (shown in the Appendix of this paper) is deliberately somewhat vague, imitating the instructions often given to engineers by customers. The students are told that the owner is not an engineer, and therefore the students need to communicate with the business owner in terms that he or she can understand. Students also write a simple program to acquire data from the transducer in the laboratory, and they test the entire system to verify its functionality.

Prior to beginning this exercise, students are prepared through lectures on the design of load cell transducers using strain gauges. A technician from a leading manufacturer of strain gauges is invited to demonstrate gauge bonding techniques, and in a previous lab, students have mounted and tested a single gauge, using a commercially available bridge amplifier and readout unit (Vishay Micro-Measurements™ P3). Students are given foil strain gauges as needed; the gauges are supplied, highly discounted, by Vishay. The experiment is conducted in a mechatronics laboratory in which DC power supplies, digital voltmeters, and personal computers are available.

The students are required to document and submit their transducer designs after the first week of the exercise, providing an opportunity for correction of serious design problems before the sensors are fabricated. The transducer designs are reviewed and graded by faculty and students are given feedback quickly, so that several days are available for the students to improve their designs before construction and testing. During the laboratory sessions in which students design, build, and test their transducers, faculty act as coaches and consultants to assist the students' projects and their learning.

In the 2010 course, students were guided toward designing load cell transducers configured as circular aluminum rings because aluminum rings of various sizes were readily and inexpensively available from the department machine shop. Some student teams whose members had machine shop experience chose to design and fabricate transducers of other types, such as a C-shaped transducer which had multiple attachment points to allow its range to be adjusted and an S-shaped transducer which was similar to some commercial designs.

The load cell transducers designed by the students must transform externally applied forces into a measurable voltage. Such transducers consist of a structural frame with several strain gauges attached. In a common embodiment, shown in Figure 1 below, the structural frame is a circular ring, and the force is applied across a diameter of the ring. Strain gauges are placed inside and outside the ring such that two gauges (1 and 4) experience compressive strain when the force is in the direction shown while the other two gauges experience tensile strain. The gauges are connected in a full Wheatstone bridge circuit, with the excitation voltage V_{EXC} applied at one node and the bridge output measured as a voltage difference (V_A - V_B).

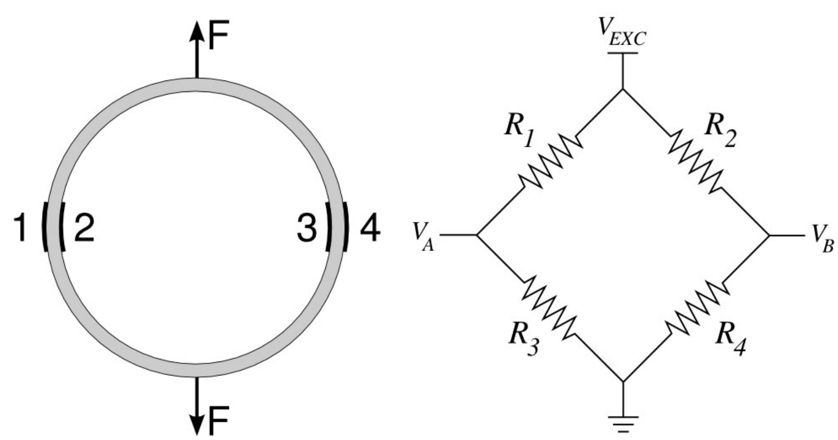

Figure 1: Diagram of a ring-type load cell transducer (left) and the Wheatstone bridge for the strain gauges (right). The applied force is F, and the strain gauges, whose resistances are R_1 - R_4, are at the corresponding locations 1-4 for a full bridge of four gauges.

The moment M in the uniform thin metal ring of Figure 1 at the strain gauge locations can be computed as[4]:

$$M = FR/2 (\cos \theta - 2 / \pi)$$

where R is the ring radius and the angle θ is zero at the gauge locations shown. The strain ε to be measured at each gauge location shown is computed as

$$\varepsilon = \pm FRt/4I (1 - 2 / \pi)$$

where t is the radial thickness of the ring and I is the area moment of inertia of the ring cross section. Students must design their transducers so that the strain ε at each gauge is large enough to be measured with good accuracy, but the corresponding stress is not high enough to risk yielding the material of which the ring is made. In keeping with the model construction principle, a key deliverable is the implementation of the design algorithm, usually in a spreadsheet, rather than the application of a formula to just one problem.

The students' performance from the first run of the transducer MEA exercise in Winter 2010 showed a typical variation in quality, but the results were encouraging in that all teams successfully created functioning prototypes, and most teams produced workable programs for transducer design and documented their work in at least a recognizable manner. A design spreadsheet created by one student team is shown in Figure 2 below, and photographs of some completed transducers are shown in Figures 3 and 4 below.

Known		Input Dimensions			Stress		Strain	
Force [lbf]	E [psi]	Radius [in]	Thickness [in]	Width [in]	Outside [psi]	Inside [psi]	Outside [micro]	Inside [micro]
5	1.00E+07	2.00	0.0625	0.75	-3667.7	3774.3	-366.8	377.4
15	1.00E+07	2.00	0.0625	0.75	-11003.0	11323.0	-1100.3	1132.3
25	1.00E+07	2.00	0.0625	0.75	-18338.4	18871.7	-1833.8	1887.2
35	1.00E+07	2.00	0.0625	0.75	-25673.8	26420.4	-2567.4	2642.0
45	1.00E+07	2.00	0.0625	0.75	-33009.1	33969.1	-3300.9	3396.9
55	1.00E+07	2.00	0.0625	0.75	-40344.5	41517.8	-4034.4	4151.8
65	1.00E+07	2.00	0.0625	0.75	-47679.8	49066.5	-4768.0	4906.7
75	1.00E+07	2.00	0.0625	0.75	-55015.2	56615.2	-5501.5	5661.5
85	1.00E+07	2.00	0.0625	0.75	-62350.6	64163.9	-6235.1	6416.4
95	1.00E+07	2.00	0.0625	0.75	-69685.9	71712.6	-6968.6	7171.3
105	1.00E+07	2.00	0.0625	0.75	-77021.3	79261.3	-7702.1	7926.1

Figure 2: Load cell transducer design spreadsheet created by a student team.

All of the teams except for one understood that they had to develop a program that was general enough to size a transducer for a variety of different forces. Many did not do an adequate job explaining exactly how to use their programs, and at least four of them ended up creating excessively large rings – up to 20 inch diameter – for the low required loads and small application. Several of the teams applied excellent design skills by writing their programs to use nominal pipe sizes from a local supplier.

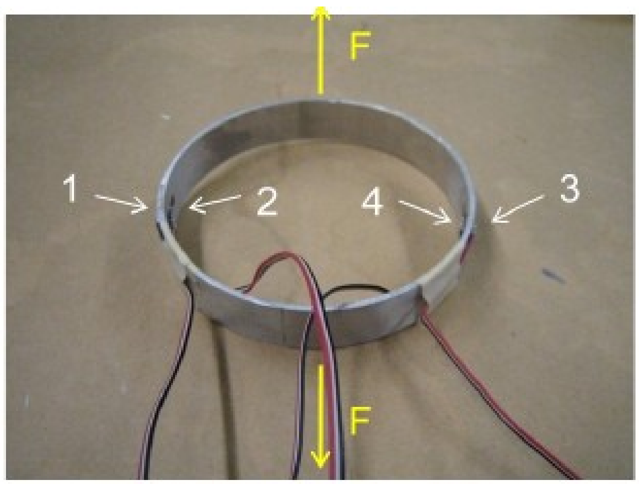

Figure 3: A ring-type load cell transducer designed and built by a student team. The arrows labeled F show the location of the applied force, and the numbers show the positions of the strain gauges.

Figure 4: Load cell transducers designed and built by students with "C" and "S" shapes. The "C" design functions in two force ranges and the "S" design is similar to some commercially sold transducers.

The quality of documentation produced by the students was somewhat less satisfying than the quality of their transducer designs and implementations. Six of the seventeen student teams did an excellent job writing the memo to the client. Many thanked the company for the opportunity to work with "Rehab-o-Rama" and were careful to write the memo to a non-technical audience. Four of the student teams turned in a typical laboratory assignment with no reference to the actual client. The remaining seven student teams attempted to address the client, but their memos were often too technical for a typical business owner or did not explain their techniques sufficiently.

The authors believe that by the time they enroll in this Senior level course, most students have well developed analysis and design skills, but they have not had as much opportunity to practice skills related to understanding the needs and motivations of a customer. Such skills are also taught in the Senior design capstone course, but most students in the mechanical measurements course have not begun, or have only just begun, work in the Senior design course at the time they complete this assignment. The students have practiced writing short technical reports and memos in many laboratory courses prior to this one, and some tend to revert to writing the type of report with which they are familiar.

Transducer Exercise and MEA Criteria

The transducer exercise meets the Reality Criterion because the problem is posed as if by a professional customer and because the need for an engineered solution follows clearly in a way that students can understand. Because students beginning the exercise have already learned concepts of statics and mechanics of materials as well as the operation of strain gauges, they are required to extend their knowledge by a reasonable amount in order to fully understand how to produce a good solution to the problem. The Model Construction Principle is followed because students must use principles of loading, stress, and strain correctly in order to design a working algorithm for transducer design. In order to meet the Self-Assessment Principle, the need to create a functioning prototype and compare the measured performance of the prototype to previously calculated predictions of the prototype's performance give the students an unambiguous way to assess their success in meeting the exercise objectives.

The Documentation Principle is met by requiring students to present written reports as well as an oral presentation in a professional format. Additionally, students must create program code, document that code, and design and test their hardware. The students' learning for this exercise meets the Generalizability Principle in that the students have demonstrated the ability to design a load cell transducer which can be scaled to a range of sizes; the concepts they must have used apply to piezoresistive load cells of many configurations. Finally, the Effective Prototype Principle is satisfied as students must work directly with stress and strain on both a theoretical and laboratory basis, reinforcing these concepts in the students' memory; the use of stress and strain in design is fundamental to a wide range of mechanical engineering problems.

Accelerometer MEA Exercise

In this MEA, students take on the role of consulting engineers hired by the fictitious “Obispo-Orlando Package Service” (OOPS) to help the shipping company choose a packaging material. Materials are to be chosen based on their ability to minimize accelerations as packages impact a hard surface. The accelerations are measured using piezoelectric accelerometers on a test setup which is provided to the students in the laboratory. In contrast to the load cell transducer MEA, the accelerometer MEA teaches experimental measurement but not design, as the students are asked to evaluate a set of packaging materials but not to design a system.

Preparation for this MEA includes lectures and homework assignments in which the students learn about the design of accelerometers and the strengths and weaknesses of piezoresistive (MEMS) and piezoelectric accelerometers. The student teams are supplied with a test setup consisting of a simple pivoting beam with an accelerometer mounted at the end[5] as shown in

Figure 5. Data acquisition for the accelerometer MEA is performed with inexpensive microcontroller based data acquisition cards controlled via a very simple LabView™ interface. Before taking data, students must verify the calibration of the accelerometer and are expected to find an appropriate method to do so (a 2-g rollover calibration is a convenient and sufficient method).

An example acceleration *vs.* time plot[6] is shown below in Figure 6. The accelerometer MEA was performed in a single 3-hour laboratory session, with analysis and reporting done as homework. Due to the time constraints, not all teams were able to acquire good data, though most were. Following the accelerometer MEA, the students were given a survey to collect some of their opinions about the transducer and accelerometer MEA's.

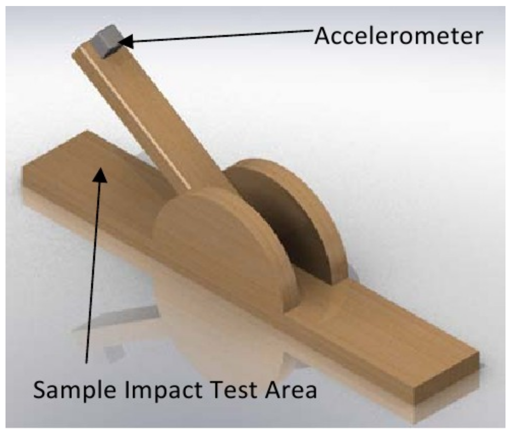

Figure 5: Impact test device for the accelerometer MEA, as modeled by a student team.

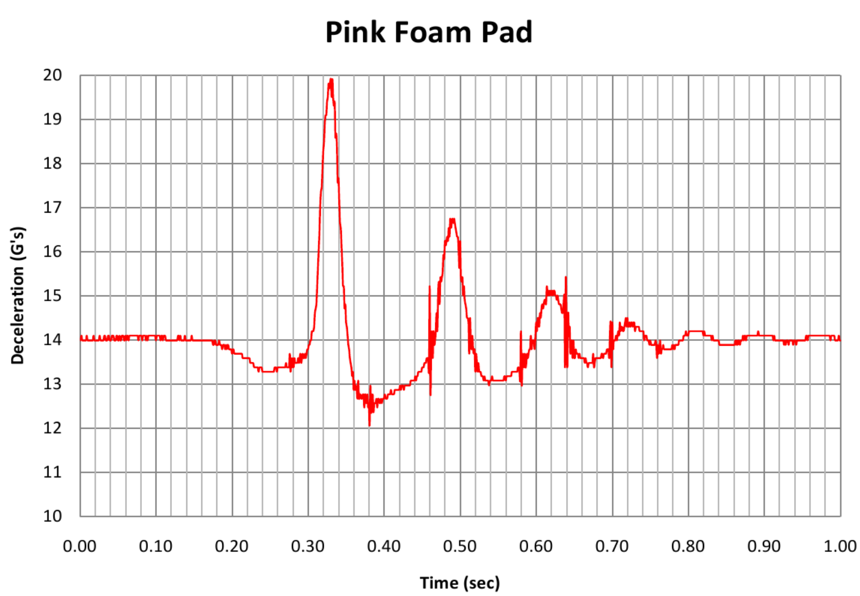

Figure 6: Acceleration vs. time measured by a student team for a packaging foam impact test.

Accelerometer Exercise and MEA Criteria

The accelerometer exercise meets the Reality Criterion through the presentation of the problem by a simulated professional client and the expectation that students present their work as if to a professional client rather than to a faculty member. The Model Construction Principle is met by the requirement that students verify the calibration of their accelerometers through calculations as well as finding a formula for the impact velocity of the test machine onto the packing material samples. The Self-Assessment Principle is met as the students use commonsense reasoning and simple analysis to verify the accuracy of their results.

In order to satisfy the Model-Documentation principle, the exercise requires students to write a memo to the customer and give a short oral presentation describing the results of their work. The applicability of accelerometer based measurement techniques to a wide range of problems involving impact enables the exercise to meet the Generalizability Principle, and the Effective Prototype Principle is met as the exercise requires the students to apply basic dynamics as well as an understanding of accelerometers in order to successfully complete their work.

Survey of Student Opinions

A short survey was given to the students in Winter 2010 to assess their views about the MEA's. The students indicated their level of agreement with two statements:

1. “The transducer lab (ring transducer) tried to use a simulated industrial client. Instead the instructors should just tell the students to build a force transducer.”
2. “Writing the memo to the client helped me think about and prepare to work with engineering customers in the workplace.”

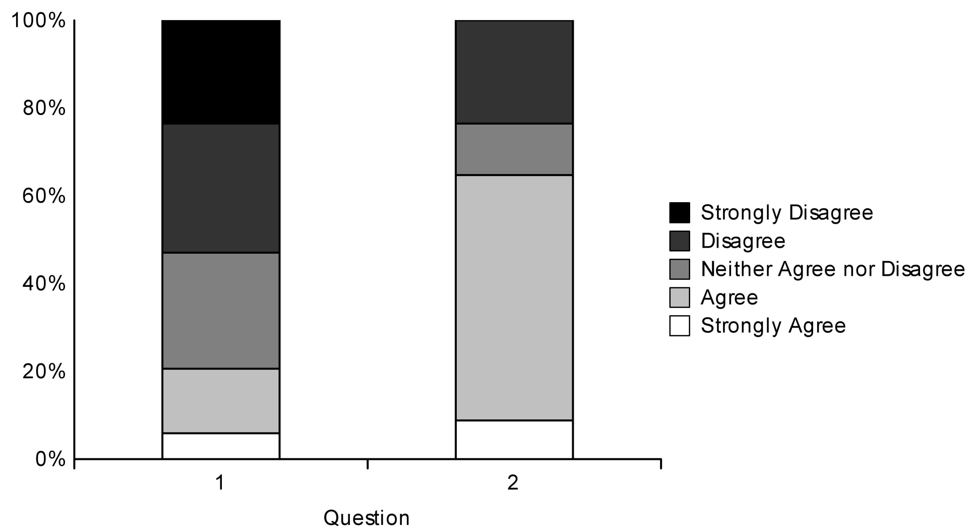

Figure 7: Responses to two survey questions about the perceived value of the simulated customer in the MEA's. In the first question, disagreement is supportive of the MEA, while in the second agreement supports the MEA over more traditional instructional techniques.

The first statement was intended to test whether the students felt that the MEA was a less valuable assignment than a more traditional assignment without the simulated client. 52% of the respondents disagreed or strongly disagreed with the first statement and 20% agreed; because the statement is written so as to reflect negatively on the MEA, this response suggests a preference by the students for the MEA rather than a more traditional cookbook approach. 65% of the respondents agreed or strongly agreed with the second statement, while 23% disagreed, none strongly. Taken together, the results of the two survey questions indicate that most students recognized the need for the use of good communication skills in the MEA assignment. Given that most of our engineering students typically show resistance to learning such "soft skills" as written and oral communication, these survey results are encouraging in that they indicate that many students have been to at least some degree won over.

When asked to write comments, many students provided insightful suggestions. Several showed their appreciation of communicating with fictitious customers with comments such as, "I thought that the customers were fun and creative. It forced us to think outside the box a little, and address them like people with potentially little technical background." Others had a bit more difficulty with the task of writing to a customer rather than faculty: "I guess that I personally didn't write it to the client, so maybe put more emphasis on writing it to the client. I kind of think you emphasized it enough, I'm just trained to do it another way and probably should break that habit." A few students disliked this aspect of the assignment, though the reasoning was not made entirely clear; for example: "Don't use customers it does not seem to translate well." The balance of the comments are seen as reinforcing the value of the MEA's.

Conclusions

It is the opinion of the authors that Model Eliciting Activities can help faculty design projects which efficiently facilitate student learning of technical skills, teaming skills, and project management skills. Although it was not possible to conduct a direct assessment which compares the efficacy of the MEA with that of traditional teaching methods or traditional PBL, the success of the students in completing the assignments and reporting their results is believed to be strong evidence for significant learning.

Some lessons learned during the transducer and accelerometer MEA's will be applied when the mechanical measurements course is next taught in 2011. Preparing the students well before the MEA commences is critical to ensuring that the projects are successful academically and that the students successfully complete the assignment. The preparation given the students during the 2010 course was shown to be successful in that the student teams all succeeded in producing transducers which had basic functionality, but better preparation can be expected to lead to more consistent student success. For example, if students have less trouble with the application of stress and strain equations to design and with the mechanics of installing and wiring strain gauges, they should be able to more consistently produce memos and presentations of good quality. To that end, the students will be assigned more closely targeted pre-lab exercises, including a homework exercise in which they design a single load cell transducer so as to gain experience with the design equations.

The construction of load cell transducers is a challenge for many mechanical engineering students because of the need to mount strain gauges and wire the gauges into a Wheatstone bridge circuit. The gauges chosen for the class, Vishay Micro-Measurements™ model EA-13-060LZ-120/E, are quite small, with an active length of about 1/16 inch (2 mm); small gauges were chosen by the instructors to allow the construction of small transducers and minimize problems caused by the averaging of strain over the length of each gauge. In retrospect, we overdid it. The small gauges were difficult for students to accurately mount, especially in a constrained location such as the inside of a transducer ring. Soldering to the small pads on the gauges was even more difficult, resulting in a lot of rework and many wasted gauges. In the future we plan to use larger gauges of about 1/8 to 1/4 inch (3 to 6 mm) active length.

Acknowledgements

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Appendix: Transducer Design Assignment Memorandum

TO: Cal Poly Design Team
FROM: Rehab-o-Rama
SUBJECT: Force readings and counters for new rehab equipment

As the population ages, more and more people require rehabilitation equipment. This includes different exercise machines as well as simple elastic bands that can be used during resistance exercises. Unfortunately we have found that many of our patients are non-compliant – they often do not perform as many exercises as needed and/or they do not achieve the proper force levels for satisfactory progress.

We want to differentiate our products from others on the market by having them (a) beep when the desired force amount is reached and (b) count the number of cycles that the patient completes. Our equipment ranges from wrist and finger exercises up to squat types of exercises, so we probably need different sized devices to get the accuracy that we desire.

One of the players on my softball team went to Cal Poly and says that small companies like yours can help us develop our product. He suggested using a ring-type transducer (whatever that is), but I don't really care what you design as long as it works. To begin our collaboration, we would like you to provide us with a way to calculate the dimensions of our transducer depending on the load we want to measure (say between 5 and 100 pounds). We are hoping for about 5% accuracy on these readings. Also, we would like you to make us a prototype of one of these transducers to test out. Once we see how your prototype works out, we'll decide if we want to hire you to program the device to calculate loads and the number of reps the patient completes.

Appendix: Accelerometer Impact Measurement Assignment Memorandum

Obispo-Orlando Package Service
123 Cardboard Court
San Luis Obispo, CA 93400

Dear CP Engineers:

Obispo-Orlando Package Service is an innovative company which specializes in deliveries from San Luis Obispo, CA to Orlando, Florida and nowhere else. Our motto is, "We don't go anywhere else, so your package can't get lost." We also constantly strive to prevent damage to packages, and we need your help in testing packaging materials so that we can find which materials best prevent damage to our customers' shipments.

Please develop a test protocol to determine which of the readily available packaging materials will create the best protection for package contents. Some samples of materials are provided for your convenience; please feel free to suggest other materials as well. We have hired a new technician, Mr. Stanley Nerdbaum, who was recently fired by his previous employer for "being a girly man and not going to the gym every day." Mr. Nerdbaum has provided some equipment which you may use in your work and made the following suggestions which may be helpful to you as you design and test your test plan:

> "Our goal is to minimize the acceleration experienced by items which impact the insides of containers. You can measure this acceleration with an accelerometer attached to an impact control system; the accelerometer should be dropped from a starting angle of 45° for consistent results. A provided USB-6008 data acquisition system can be used to digitize data. You should use the *Measurements and Automation System* icon in Windows™ to test the USB-6008. Try the self-test as well as the test panel. Refer to the provided paper handout for more guidance. You will need to create a new Labview program to do the tests. I recommend that you use the Labview *Daq Assistant* function in the back panel to read data from the USB-6008, then add a graph to the front panel and a function to the back panel which saves data to a spreadsheet file. When your program is working, you need to calibrate the accelerometer. Perhaps a 2-g rollover test will work (I'm not sure if it will). You may need to do a web search to get a datasheet for the accelerometer you're using or a similar model."

When you have finished your experiments, please submit to Oops a report which contains at least the following:

- A one-page to two-page memo explaining your test plan and describing your findings
- A table with peak G's for at least 3 tests for each material
- An example acceleration-*vs*-time plot for an impact
- Calculations (neat and readable hand calculations are sufficient) which show the impact velocity of the pendulum on the test material

Thank you for your assistance in helping us to make our company the leader in SLO-Orlando specific package delivery market.

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